THEORETICAL MODELS OF ACTIVE GALACTIC NUCLEI +

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ABSTRACT

We review attempts to incorporate radio sources within the context of general models of active galactic nuclei. The behaviour of gas accreting onto a massive black hole depends upon its angular momentum and accretion rate. It is argued that radio galaxies, QSR's and QSO's (and Seyfert 1 galaxies) be associated with increasing mass accretion rates $\dot{M}/M$. The classification of an active galaxy appears to be aspect-dependent. In particular BL Lac objects, OVV quasars and the superluminally expanding compact sources appear to be beamed towards us. We show how the choice of source model can influence the statistics of beaming.

1. INTRODUCTION

Substantial advances have been made over the past few years using the techniques on conventional, radio-link and Very Long Baseline Interferometry. Extragalactic radio sources, previously divided into the "compact" and the "extended" are now all widely attributed to the dissipation of an underlying supersonic jet. The one-sidedness, common in the VLBI observations and in VLA maps of the more powerful extended sources is naturally explained as a consequence of relativistic beaming as first suggested by Rees (1966) and Shklovsky (1968). This view is strengthened by the measurement of superluminal expansion (Cohen, these proceedings) and the discovery, reported here by Perley, that the large scale jet in Cygnus A is very narrow and therefore presumably light and fast. More speculative, detailed models, necessary to confront the improved dynamic range of the radio maps, have difficulty in accommodating all the observational evidence (Scheuer, these proceedings). However, in this reviewer's opinion, relativistic jets still provide the correct physical framework for discussing compact radio sources.

Radio emission forms only one, often energetically insignificant, aspect of the general phenomenon of galactic nuclear activity. It is

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R. Fanti et al. (eds.), VLBI and Compact Radio Sources, 215–225.
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then natural to try to interpret radio emission in the context of the total electromagnetic spectrum and to suggest which aspects of a galactic nucleus dictate whether it will form a Seyfert 2, QSR etc. In this review we summarise some recent work pertaining to accretion onto hypothetical massive black holes, describe some of the consequences of relativistic beaming and suggest a possible physical classification scheme for active galactic nuclei.

2. ACCRETION ONTO MASSIVE BLACK HOLES

Radio jets appear to be the hot exhaust gases escaping from the central engine. In recent years this engine has most commonly been modelled as a massive black hole. Although no single observation requires this, several observations (central light cusp and rise of velocity dispersion, rapid X-ray variability, persistence of jets etc.) are naturally interpreted in these terms and a black hole is at least the probable evolutionary end point of alternative candidates like spinars, multiple stellar mass black holes (Pacholoczyk and Stoeger 1983) and starburst nuclei

Much theoretical work has assumed spherical symmetry (e.g. Maraschi and Treves 1982). Although this poses genuine formal challenges, we know that it connot account for the production of jets, just as an axisymmetric magnetosphere cannot account for radio pulsars. (The discovery by Stockman, Angel and Miley (1980) and Antonucci (1983, preprint) of a correlation between the optical polarisation direction and the radio source axis in quasars and Seyferts implies a direct relationship between the jet and the continuum producing region.) Spherical infall models can account roughly for the infrared optical continuum if the mass accretion rate is roughly critical ($\dot{M} \sim \dot{M}_E \sim 4\pi MG/\kappa_T c$) and the flow is sufficiently dissipative and magnetised. In this case the mildly relativistic electrons near the hole can radiate low harmonic synchrotron radiation at a frequency in the far infrared where the source becomes optically thin. These infrared photons can then be Fermi-accelerated by the mildly relativistic electrons (which necessarily have a Thomson optical depth of order unity) to produce a power law spectrum. (e.g. Takahara, Tsuruta and Ichimaru 1981, Schmid-Bergk 1978, Ipser and Price 1982). These models may have difficulty in accounting for the flatter UV and X-ray spectra as well as the steadiness of the observed emission over thousands of dynamical timescales.

Accretion flows with angular momentum are generally argued to be axisymmetric about the spin of the hole as a consequence of Lense-Thirring torques (e.g. Thorne and Blandford 1982). At moderate accretion rates ($\dot{M} \sim \dot{M}_E$) the inflowing gas can cool and should settle into a disk. The structure of this disk is dictated by the unknown viscosity but it is probably radiation-dominated and thermally unstable in its innermost parts (e.g. Pringle 1981).

Quasars and Seyfert 1 galaxies appear to have UV excesses which have been modelled as a black body with temperature $\sim$ 25,000 K which Malkan (1983) has interpreted as radiation from the surface of a thin disk. This requires that the black holes be extremely large ($M \gtrsim 10^9 M_\odot$) and unfortunately in the case of the radio quasars predicts linear polarisation orthogonal to what is observed. A large fraction of the power liberated by the gas as it spirals inwards may be dissipated in a tenuous corona above the disk. This is of interest because Seyfert 1 galaxies and quasars seem to radiate from $\sim$ 0.1 to $\sim$ 0.5 of their bolometric power as hard ($\gtrsim$ 50 keV) X-rays or γ-rays. If the source spectrum,perhaps created non-thermally, extends beyond 0.5 MeV then electron-positron pairs can be created and these will annihilate so as to maintain a Thomson scattering optical depth of order unity. This is an alternative route to a Comptonised power law spectrum (Guilbert, Fabian and Rees 1983, preprint). Electron-positron pairs, unencumbered by proton inertia can be blown off by radiation pressure and may ultimately be collimated to form a jet. Jets may also be launched and collimated by magnetic torques acting upon the disk. If the poloidal field emerging from the surface of a Keplerian disk makes an angle of less than 60° with the radial direction then gas will be flung out along the field lines. As it moves radially outwards, its inertia will cause the field to become increasingly toroidal and thereby create a magnetic pinch (Blandford and Payne 1982).

When the accretion rate is increased ($\dot{M} \gtrsim 10\ \dot{M}_E$) radiation pressure can inflate the inner disk and produce a radiation and rotation supported torus (e.g. Jaroszyński, Abramowicz and Paczyński, 1980). Within this torus, the gas pressure is negligible and electron scattering opacity predominates. The diffusive heat flux must therefore be $-\underline{g}c/\kappa_T$ where $\underline{g}$ is the local effective gravity and κ_T the Thomson opacity. A radiation torus may be analogous to a giant early-type star, possessing a core around the pressure maximum where most of the binding energy resides, and an extensive envelope bounded by a photosphere. A radiation torus need not accrete gas steadily and if it is established by a very rapid episode of fuelling, it may settle down to a quasi-static configuration slowly deflating on a thermal timescale as photons diffuse outwards at roughly the Eddington limit. If the torus is large enough, the effective temperature can fall to a limiting value $\sim$ 25,000 K where Helium recombines and the opacity changes rapidly. It is tempting to associate this with the UV excess. Radiation tori are similar in many regards to the massive objects originally postulated by Hoyle and Fowler and may suffer the same fate - i.e. be shown to be dynamically unstable. There are possible axisymmetric local instabilities caused by unfavourable entropy and angular momentum gradients (e.g. Seguin 1975, Kandrup 1982). These presumably evolve to create marginally stable convection zones just as in a star. More threatening are non-axisymmetric instabilities. Papaloizou and Pringle (1983, preprint) have recently demonstrated that a toroidal configuration known to be marginally stable to axisymmetric disturbances possesses global, non-axisymmetric dynamical instabilities. It will apparently destroy itself in a few orbital periods unless non-linear terms can saturate the instability at a low amplitude. It is not yet known if this is a general property of these tori. Furthermore, it is not at all clear that tori can evolve towards stable or marginally stable states even if they exist and that the rate of internal energy generation through viscous dissipation can always be balanced by heat transport.

The most relevant property of radiation tori to extragalactic radio sources is that they possess funnels. It has been widely speculated that this is the site of jet collimation. This idea seems difficult to sustain because most of the observed radio jets are associated with comparatively faint galactic nuclei. They are certainly not radiating at anything like the Eddington limit of a $10^8 M_\odot$ black hole (10^{46} erg s^{-1}). Furthermore it seems that radiation drag prevents the outflow from ever being relativistic and well collimated (e.g. Sikora and Wilson 1981). This does remain a possible mechanism for jet production in the case of radio quasars that are not known to be superluminal (and also in SS 433) but there seems to be no need to invoke a separate mechanism in these cases. When the energy production becomes very large the radiation may be trapped in an outflowing optically thick jet perhaps collimated through a pair of nozzles (Begelman and Rees 1983).

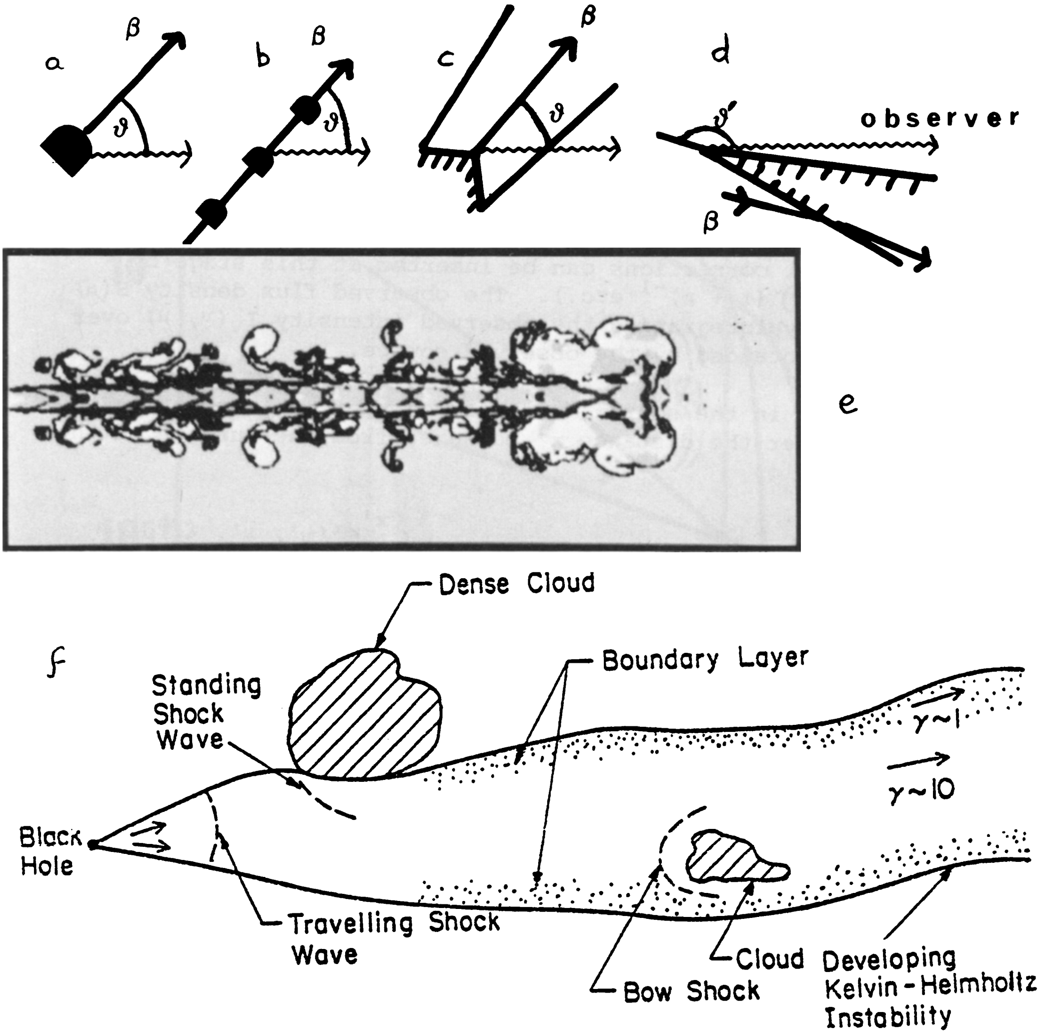
When the accretion rate falls below the Eddington value then most of the power released may be extracted electromagnetically from the spinning black hole by an axisymmetric magnetic field held in place by a disk or ion-supported torus (e.g. Thorne and Blandford, 1982). The details of this mechanism have been investigated further by MacDonald and Thorne (1982) and Phinney (1983). In particular, it has been shown that if the magnetosphere contains plasma that is free to move along the field, then inertial effects reduce the maximum extractable energy from roughly fifteen per cent of the rest mass of the hole to roughly three per cent. Nevertheless, this is still ample to supply the minimum energy requirements of all known radio sources with black holes of mass $M \lesssim 10^9 M_\odot$. One major problem with this mechanism is to understand the interaction of the orbiting gas with the field that it encircles. This is crucially different from the analogous problem with an accreting magnetised neutron (e.g. Ghosh and Lamb 1978) because the magnetic geometry will not cause accreting gas to flow to high latitude around a black hole. Most of the magnetosphere should therefore be quite low density which is a necessary condition for this mechanism to operate.

For further details on these and related models see Rees, Begelman and Blandford 1981, Rees 1982, Blandford 1983.

3. BEAMING

As is well known, the discovery of superluminal expansion within compact radio sources suggests that they involve relativistic outflow and this in turn implies that the radio emission is highly anisotropic (e.g. Scheur, these proceedings). Our classification of a particular radio source is then strongly influenced by our orientation with respect to it.

Figure 1. Simple models of emission features of compact radio sources a) Individual plasmoid moving with speed β along a direction making an angle $\theta = \cos^{-1}$ to the line of sight. b) Several identical plasmoids or equivalently an optically thin jet. c) Conical shock wave (with cone angle 51°) moving with speed β 0.99 through a non-relativistic jet seen at a given coordinate time in the jet frame. d) The same, but seen in the frame in which the shock structure is at rest. Rays destined for the observer are emitted along a direction making an angle $\theta' = \cos^{-1}\mu'$ to the axis. The observer sees the projection of the shape of the shock structure on a plane normal to this direction. e) Numerical simulation of an axisymmetric jet kindly supplied by Drs. Norman, Smarr and Winkler. The Mach number is 3 and the jet density is one tenth that of the surroundings. The dark crosses are strong shock waves. f) Schematic representation of features likely to be present in a real jet.



In particular, the powerful compact radio sources are postulated to be beamed in our direction. In order to test this idea quantitatively and to determine the nature of the unbeamed objects it is necessary to have a model of the emitting region. To date, most models have been far simpler kinematically than we can reasonably expect the sources to be (see Fig. 1). They can also be misleading.

The prototype is a plasmoid moving uniformly with speed $\beta c = (1 - \gamma^{-2})^{\frac{1}{2}} c$ at an angle $\theta = \cos^{-1}\mu$ to the observer direction. The observed velocity on the sky in units of c is $\beta_0 = \beta(1 - \mu^2)^{\frac{1}{2}}(1 - \beta\mu)^{-1}$ which can be as large as $\gamma\beta$. Now assume that the plasmoid is unchanged as it moves. Radiation destined for the observer is emitted in the plasmoid frame at an angle $\theta' = \cos^{-1}\mu'$ to the velocity where $\mu' = (\mu - \beta)(1 - \mu\beta)^{-1}$. The shape seen by the observer in his frame is simply the projection of the plasmoid seen from the angle θ' in its frame as may readily be verified by Lorentz transformation (e.g. Terrell 1966). So, in order to evaluate the observed flux and brightness, we must evaluate the intensity $I'_{\nu'}(\nu', \mu')$ in the source frame and Lorentz transform it into the observer frame using

$$I_\nu(\nu, \mu) = \mathfrak{D}^3 I'_{\nu'}(\nu' = \nu/\mathfrak{D}, \mu') = \mathfrak{D}^{3+\alpha} I'_{\nu'}(\nu, \mu')$$

where $\mathfrak{D} = \gamma^{-1}(1 - \beta\mu)^{-1}$ is the Doppler factor and α is the spectral index (Cosmological corrections can be inserted at this stage by replacing $\mathfrak{D}$ with $\mathfrak{D}(1 + z)^{-1}$ etc.). The observed flux density $S(\mu)$ is then obtained by integrating the observed intensity $I_\nu(\nu, \mu)$ over the solid angle subtended by the observed source.

The intensity in the source frame is computed by integrating the emissivity $j'_{\nu'}$ over the distance x' measured from the surface of the source.

$$I'_{\nu'}(\nu', \mu') = \int dx'\, j'_{\nu'}(\nu', \mu', x') e^{-\int^{x'} \kappa'(\nu', \mu', \xi') d\xi'}$$

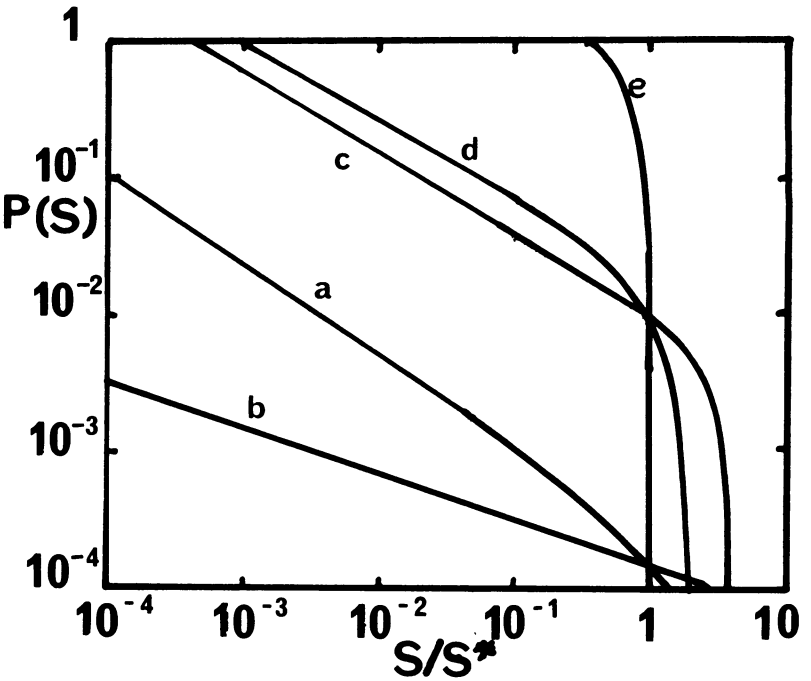
where

$\kappa'(\nu', \mu', x')$ is the absorption coefficient.

For an optically thin source at distance D, $S = D^{-2} \mathfrak{D}^{3+\alpha} \int j'_{\nu'}(\nu, \mu', x)\, dV' \propto (1 - \beta\mu)^{-(3+\alpha)}$ where V' is the proper volume of the source (This expression is incorrect if the source varies or there is absorption.)

A useful way to quantify the degree of beaming inherent in a particular model is to compute the probability P(S) that we are oriented so as to observe a flux density in excess of S. For individual plasmoids whose emissivity changes slowly on their light crossing times, it takes an interval $dt_0 = \mathfrak{D}^{-1} dt'$ of observer time to receive radiation emitted in an interval dt' of source proper time. As S increases monotonically with μ,

Figure 2. Probability that the flux density from a given source will exceed a value S for five different models considered in the text. In all five models the emitting features move with space velocity $\beta = 0.99$ and $\alpha = 0$. The flux is normalised to the value S that would be observed from an angle $\cos^{-1}\beta$ where the features could be observed to move with their maximal superluminal velocity $\beta_o = 7.0$ in all except case (b) where the normalisation is arbitary.
a) Individual plasmoids of constant power. b) Individual plasmoids in which the spectral power varies as the inverse cube of radius. c) Superposition of many plasmoids (or steady jet). d) Superposition of plane shocks moving along a non-relativistic jet. e) Superposition of conical shocks moving along a non-relativistic jet. The cone angle in the frame of the jet is 51°.



$$dP(S) \propto (1 - \beta\mu)d(1 - \mu), \quad 0 \lesssim \mu \lesssim 1$$

$$P(S) = \frac{(1 - \beta)^2}{2\beta}\left[\left(\frac{S_{max}}{S}\right)^{\frac{2}{3+\alpha}} - 1\right] ; \quad (1 - \beta)^{3+} S_{max} < S < S_{max}$$

See Figure 2. (We ignore plasmoids moving away from us).

In computing this distribution, we have assumed that each plasmoid has constant emissivity in its frame for a fixed proper time i.e. in moving over a finite range of radius. However, suppose for example, that the source weakens as a power of radius.

i.e. $S \propto r^{-n} (1 - \beta\mu)^{-(3+\alpha)}$ as the radius increases by a factor $\gg \gamma^{\frac{2(3+\alpha)}{n}}$.

The source can then be seen out to a radius $r \propto S^{1/n}(1 - \beta\mu)^{\frac{-3+\alpha}{n}}$. The probability of observing a source with flux greater than S satisfies

$$P(S) \propto \int r(1 - \beta\mu)d(1 - \mu)\ S^{-1/n} \propto \int (1 - \beta\mu)^{1 - \frac{3+\alpha}{n}} d\mu$$

In this case, the slope of the P(S) variation is dictated by the radius exponent n. Furthermore, if $n > 3+\alpha$, then a flux-limited sample will be dominated by jets moving away from us!

In these two examples, we have only included those sources that we can see and we preferentially omit those beamed towards us because we observe them for a relatively shorter time than those moving with larger angle θ. Now, the cores of core-jet sources appear to be permanently bright and might therefore comprise a sum of several plasmoids which can merge together to form a continuous jet. In this case we have a stationary pattern through which the synchrotron-emitting plasma is flowing. If we do not observe individual features then there will be no superluminal expansion. The emissivity and absorption coefficient must be transformed from their values in the frame co-moving with the plasma and designated with a bar

$$j_\nu(\nu, \mu) = \bar{j}_{\bar{\nu}}(\bar{\nu} = \nu/\mathcal{D})\mathcal{D}^2$$

$$\kappa(\nu, \mu) = \bar{\kappa}\ (\bar{\nu} = \nu/\mathcal{D})\mathcal{D}^{-1}$$

The emergent intensity can then be computer from the equation of transfer. For an optically thin source, the flux is $S = D^{-2}\ \mathcal{D}^{2+\alpha} \int dV\ \dot{j}_{\bar{\nu}}(\nu) \propto (1 - \beta\mu)^{-(2+\alpha)}$ and

$$P(S) = (1 - \mu) = \left(\frac{1 - \beta}{\beta}\right)\left|\left(\frac{S_{max}}{S}\right)^{\frac{1}{2+\alpha}} - 1\right| \ ; \ (1 - \beta)^{2+\alpha}S_{max} \lesssim S \lesssim S_{max}$$

The flat spectra of compact sources are probably caused by the superposition of self-absorbed synchrotron spectra. Simple jet models (e.g. Blandford and Königl 1979, Reynolds 1983) are very similar to optically thin sources with $\alpha = 0$.

Already, these three models make quite different predictions about the nature and number of the unbeamed sources. A somewhat more realistic model introduces further differences. The radio power that we observe from jets is probably derived from the kinetic energy of the flow and the most natural way to do this is with a shock wave. A shock wave necessarily introduces a difference between the velocity β of the stationary pattern which dictates the speed of observed superluminal motion and the velocity of the emitting plasma which is responsible for the Doppler boosting.

For simplicity, set $\alpha = 0$ and assume an ultrarelativistic equation of state ($p = 1/3\rho$). If the front is perpendicular and moves with speed β in excess of the sound speed $3^{-\frac{1}{2}}$ through a slowly moving jet, the post-shock velocity (in the shock frame) is $1/(3\beta)$ (e.g. Landau and Lifshitz 1969). The emissivity in the pattern frame satisfies $j'_{\nu'} \propto (1 + \mu'/3\beta)^{-2}$. As before, if there are several identical shocks, $S \propto (1 + \mu'/3\beta)^{-2} (1 - \beta\mu)^{-2}$. The emission has an angular distribution similar to that from plasmoids moving with a speed $\beta - (1 - \beta^2)/2\beta$. However, real jets are more likely to produce oblique shock waves which deflect the flow without changing its speed so much. Oblique shocks are naturally in numerical simulations of non-relativistic jets (Norman, Smarr and Winkler 1983). In the frame of the shock, the emission is beamed along the backward direction thereby making the observed emission far more isotropic. This effect can be seen quite clearly in Fig. 2 where we plot P(S) for a conical shock with cone angle 51° in the jet frame (but only 10° in the frame of the shock). Although there are $\sim 2\gamma^2 \sim 100$ sources for every one observed to have an observed speed $\beta_O \sim 7$, these sources are no more than four times fainter instead of being up to 1000 times fainter in the case of a plane shock (Blandford and Lind, 1983, in preparation).

Realistic source models should contain features moving with a range of speeds, directions and intrinsic powers, and what we observe depends upon an integration over these quantities. It is clear from the above that the observed power from an individual source can just as easily be dominated by features moving at angle $\sim 60°$ to the line of sight as by those moving at 5° and so the apparent failure to find further examples of superluminal expansion reported by Readhead in these proceedings need not be disturbing. In addition one should be cautious about making purely statistical arguments about the necessity or irrelevance of beaming in compact radio sources until we understand the source structure better (Scheuer and Readhead 1979, Browne, these proceedings).

4. GRAND UNIFIED THEORY OF ACTIVE GALACTIC NUCLEI

Unified theory interprets compact radio sources as being a small fraction of active galactic nuclei with jets pointed towards us. The association of unbeamed BL Lac objects with intermediate power radio galaxies seems increasingly attractive (Browne, 1983, Moore, Angel and Wardle 1983 preprint). However, the identification of unbeamed compact quasars with either optical or extended radio quasars is proving harder to sustain. A resolution of these difficulties is possible if we regard superluminal expansion more as a symptom of relativistic outflow and less as a measurement of the angle between the jet and the line of sight. The very attractive beaming hypothesis can then shelter behind a barricade of increasingly sophisticated source models, that are in any case necessary to interpret the maps presented here by Pearson and others (cf. § 3.)

When we try to go further and unify the powerful radio sources with the totality of active galactic nuclei, then the important unifying idea is a massive black hole. Now the light travel time across a $\sim 10^8 M_\odot$ black hole is ~ 1 hour and it is perhaps surprising that most active nuclei are steady on timescales far longer than this and we might conclude that the black holes themselves need some secluding. It is then fortunate that the three modes of accretion distinguished in § 2 probably do not allow us to view the black hole directly, either because the power is released as an essentially invisible electromagnetic energy flux or because there is an extensive electron scattering atmosphere.

The two most important parameters controlling accretion onto a massive black hole are its accretion rate in units of the Eddington value $\dot{m}$ and its mass M. Radiation tori with $\dot{m} \gtrsim 10$ and large photospheres can be associated with the optical quasars and in the case of smaller holes ($M \lesssim 10^7 M_\odot$), with Seyfert I galaxies. Their power law continua can be produced by the Comptonisation of infrared synchrotron and thermal photons by mildly relativistic electrons in a hot corona perhaps heated by radiation dominated gas flowing outwards along the funnels. Radiation tori probably accelerate a poorly collimated wind. The comparatively weak radio sources may be produced when this is decelerated within the galactic nucleus.

As the accretion rate is lowered, the disk will thin and the relative importance of non-thermal process will increase. These are the radio quasars and again for lower hole masses, the Seyfert II galaxies. At quite small values of $\dot{m}$, non-thermal mechanisms dominate and indeed most of the power may be derived directly from the hole. These are the radio galaxies. All of this can be set in an evolutionary context by noting that high accretion rates were far more common in the past.

Seyfert galaxies are associated with spirals and radio galaxies with ellipticals. A corrollary of the above identification is that spirals should generally have lower hole masses than ellipticals. In particular the brightest radio quasars are most likely to be associated with ellipticals although less powerful optical quasars may be predominantly spiral. Fur further references see Blandford (1983).

ACKNOWLEDGEMENTS

I thank the Director of the Institute of Astronomy, Cambridge for hospitality during the writing of this paper. I am indebted to Tony Readhead, Martin Rees, Peter Scheuer and especially Sterl Phinney for invaluable discussion. Financial support by the National Science Foundation under grant AST 82, 13001 and the Alfred P. Sloan Foundation is gratefully acknowledged.

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